

EMISSIONS AND ENVIRONMENTAL IMPACTS FROM CHILLERS *

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Abstract

The impacts of air conditioning and refrigeration systems on stratospheric ozone are primarily linked to release of ozone-depleting refrigerants. Their contributions to global warming stem both from release of refrigerants and from emission of greenhouse gases by associated energy use. Because the energy-related component has a higher or dominant warming impact, phaseout of the refrigerants in current use with less efficient options will have the opposite effect to that intended, namely to increase net greenhouse gas emissions. Integrated assessment of ozone depletion, global warming, and atmospheric lifetime provides essential indications in the absence of ideal refrigerants, namely those free of these problems as well as safety, stability, compatibility, cost, and similar burdens. This paper examines the trend in refrigerant losses from chiller use. It documents both substantial progress in release reductions and the technical innovations to achieve them. It contrasts the impacts of current hydrochlorofluorocarbon (HCFC) and hydrofluorocarbon (HFC) refrigerants with alternatives and with the chlorofluorocarbons (CFCs) they replaced. The paper also summarizes thermodynamic and environmental comparisons of options to show that phaseout decisions based on chemical composition alone, without regard to attributes of individual substances, may result in greater environmental harm than benefit.

Introduction

The final conclusion of the latest Scientific Assessment (WMO, 1999), the fourth in a series by an international panel of leading scientists since adoption of the Montreal Protocol, recognizes that:

“The issues of ozone depletion and climate change are interconnected; hence, so are the Montreal and Kyoto Protocols.”

This conclusion is based on meticulous consideration of the underlying atmospheric science and extensive sets of supporting data (WMO, 1999). It also follows intuitively from recognition that the phenomena of ozone depletion and climate change involve the same atmosphere (Albritton, 1997).

The primary global environmental impacts from air-conditioning and refrigeration (ACR) systems arise from emissions of refrigerants and of gases associated with energy use. Those gases usually are released at the power plants that provide the electricity, steam, or hot water used to manufacture, transport, install, operate, service, and ultimately dispose the equipment and ancillary devices. They can occur on-site when the equipment is driven by engines or turbines or with use of direct-fired absorption cycles. Of the total, releases of refrigerants and of combustion emissions to provide operating power dominate. Specifically, discharge or leakage of stable refrigerants containing chlorine, bromine, and – though generally negligible – other halogens affects the stratospheric ozone equilibrium. Likewise, both the common refrigerants and the combustion products, notably carbon dioxide (CO₂) and to a lesser extent nitrous oxide (N₂O), act as GHGs. Refrigerant re-

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leases have multiple effects, variously including ozone depletion following breakdown, direct action as GHGs, and efficiency reduction leading to increased energy use. The performance reductions occur with departures from the optimal charge or – for refrigerant blends – charge and composition. Hence, the critical issues in addressing stratospheric ozone depletion and climate change for ACR systems come down to selection of refrigerants that minimize impacts, reducing their release, and increasing net efficiencies to lower energy-related GHG emissions.

The severe consequences of ozone depletion are being averted through international adherence to the Montreal Protocol. The levels of chlorine and bromine reaching the stratosphere, referred to as chlorine-bromine loading (CBL), have peaked or are now peaking, and the ozone layer has begun or soon will start to recover (WMO, 1999). The outlook for global warming and the severity of its consequences are far more threatening. Even if releases stopped for all other GHGs, carbon dioxide emissions from energy use still would increase in concert with foreseen economic improvement in developing countries and with population growth (IPCC, 1996). Whereas the net carbon dioxide impact overshadows the combined effects of all other GHGs, reduction in energy demands and efficiency improvement are crucial. As a minimum, no changes that decrease efficiency can be deemed acceptable.

The functional measures of the Montreal and Kyoto Protocols, beyond those addressing scientific assessments and international assistance, differ. The Montreal Protocol restricts the production of the individual chemicals of concern, leading to their ultimate phaseout for most uses (UN, 1987; UNEP, 1996). The Kyoto Protocol imposes national limits on emissions of important GHGs, but does so by a collective approach encompassing six specific gases or groups of gases (UN, 1997). The most critical gas among them is CO₂. Although they have a much lower impact, namely 1.6% of the total for the USA at present (EIA, 1998), HFCs and PFCs as groups constitute two of the six GHGs in the Kyoto Protocol “basket.” Some studies project that their impact will reach 4-10% of the global total by 2100 and double that if not controlled (Ko et al., 1993).

Refrigerant Emission Reductions

A number of studies, summarized in table 1, have compiled data or estimated losses from centrifugal chillers. Some of the dates shown are estimates for studies that did not specifically identify this information. The dates for conversions, from CFCs to either R-123 or R-134a, indicate the when the conversion was performed.

The terminology of *initial*, *annual* (which includes both *operating* and annualized *intermittent*), and *disposal* losses is explained in Calm et al. (1999). All of them are expressed as a fraction of the operating refrigerant quantity, or *charge*. The disaggregation is useful to assess the timing of emissions and their impacts. Briefly:

- *Initial*: This group includes all losses associated with making equipment functional, and specifically those associated with manufacturing, performance and leak testing, transportation, installation, initial charging, field leak testing, and initial start up. These losses are very small, except in cases where a significant leak is discovered or a failure occurs during start up.
- *Operating*: Unlike the initial losses, which occur once in the life of a machine, the operating losses are recurring. They include both leakage and purge releases.
- *Intermittent*: Also recurring, these releases include those from maintenance (for example in disconnecting hoses and opening systems for major service procedures), accidents, failures, unintentional venting, technician errors, and nonspecific causes.
- *Disposal*: This amount accounts for the refrigerant lost at equipment retirement, a one-time event per machine.

The progression of leak data in table 1 shows a clear trend in release reduction, by as much as two orders of magnitude in several decades. This remarkable achievement was driven, for the most part, by growing envi-

Table 1: Chiller refrigerant losses (%/yr)

time frame and, if applicable, location (study)	initial	annual	disposal
earlier anecdotal data (Fischer et al., 1991)	—	12 - 37	—
1970s - 1980s Japan (Miyasaka, 1989)	—	2.2 - 18	—
1970s - 1980s USA (Hummel et al., 1991)	—	7.4-10.2	—
1980s USA, “historical” (Calm, 1993)	—	8	10
1987-1989 France (Climafort, 1998; Sauer, 1998)	—	12.6 - 30.6	—
1990 (UNEP 1991)	—	8 - 15	—
1990s, “parametric” (Fischer et al., 1991)	—	0 - 16	0 - 5
1990-1992 (Climafort, 1998; Sauer, 1998) ^a	—	15.3 - 18.2	—
1991 USA, “current” (Calm, 1993) ^a	—	4	5
1993-1995 France (Climafort, 1998; Sauer, 1998) ^a	—	7.9 - 10.7	—
late 1990s, “parametric” (Sand et al., 1997)	—	½ - 4	5
1996 USA (Calm et al., 1999) ^a	0.7 ^b	1.0 ^{b,c}	1.5 ^b
1992-1997 (Trane 1997) ^a	—	0.46%	—
1999 USA, manufacturer claims	—	<0.1 - <0.5 ^d	—
projected ~2000, “future” (Calm, 1993)	~0	<½	<½
<u>refrigerant conversions</u>			
1989-1993 USA (Clark, 1999)	—	0-154 ^e	—
1996 USA (Calm et al., 1999) ^a	0.7-3.5 ^b	1.0 - 10 ^{b,c}	1.5 ^b
1992-1997 (Trane 1997) ^a	—	0.62%	—

^a actual releases since 1991 are increasingly lower than indicated due to use of make-up rates as a proxy to determine loss rates (see discussion in text)

^b includes adjustments for *upstream* losses (see discussion in text)

^c annual sum of *operating* and *intermittent* losses

^d claims do not elaborate the specific losses included or how they were determined

^e several converted machines had repeated, catastrophic losses: The average for operation from 1994 through 1998 was 3.2 %/yr with exclusion of the four worst machines.

ronmental awareness, market economics including manufacturer competition to claim reduced emissions, and anticipation of refrigerant shortages and future regulations.

Most of the data from before 1990 is necessarily from chillers employing CFCs. They were used in more than 95% of centrifugal chillers, led by R-11 in approximately two-thirds. There is no reason to expect differences in leakage rates by chemical composition (for example, between CFCs, hydrochlorofluorocarbons or HCFCs, and HFCs) for equipment fabricated with similar materials and technologies. Different loss rates are likely for R-717 (ammonia) based on the materials and fabrication differences. One distinction that is likely to influence emission rates is dissimilar operating pressures.

Climafort (1998), Dazin (1998), Hummel (1991), and Sauer (1998) document higher losses, by as much as 50%, in older chillers using low-pressure refrigerants. These differences are consistent with expectations based on old purge designs, which vented appreciable refrigerant quantities along with the air removed, but they are not indicative of current and projected practice. Low-pressure chillers and refrigeration systems fitted with condensing purges coupled with vapor recovery systems, for purge venting, should offer a small advantage. Leaks,

when they occur, in the subatmospheric portion of such systems generally will suck air in, rather than release refrigerants. The purge device removes this air. A small amount of refrigerant vapor accompanies the air, but the purge condenses most of this refrigerant and returns it to the chiller. The vapor recovery canister (commonly a tank filled with activated charcoal) absorbs most of the remainder for recovery in periodic processing. The majority of R-11 and R-113 (both CFCs) retrofits and new R-123 (an HCFC) chillers employ purge and vapor recovery systems; the same advantage is expected with low-pressure HFCs or hydrofluoroethers.

Whereas the driving force in a leak is pressure differential, a shift to high-pressure refrigerants – whether HFCs, hydrocarbons (HCs), ammonia, or others – is likely to increase releases when leaks occur. There is little difference in loss rates in new, tight equipment based on design compensation, but the available data and anecdotal accounts for high-pressure refrigerants point to higher releases when failures do occur. A tiny leak will increase purge run time with almost no refrigerant loss in a low-pressure machine, but the same small opening will discharge increasing refrigerant amounts with increasing operating or standby pressure. The full refrigerant charge may be lost in a high-pressure system before a leak or rupture is detected or attended to.

The common practice of using refrigerant additions (*make-up*) and removals as a proxy for actual releases, which are difficult to measure, introduces three errors that exaggerate emissions. First, some of the make-up refrigerant in low-pressure chillers offsets amounts removed in purge venting, even though very small in tight chillers. Most of the vented refrigerant is or could be – as discussed below – recovered, but recovery usually is left out of the accounting. The actual releases, therefore, may be as much as 25% lower for low-pressure chillers where the recovery tanks are correctly reprocessed. Second, some of the initial and early make-up amounts do not reflect actual losses. The portion of the refrigerant that is not recovered from factory testing remains inside the chiller, dissolved in the lubricant or absorbed in other materials. This amount reduces startup charge requirements. Likewise, some early additions reflect original undercharging rather than actual releases. Third, replacements for contaminated refrigerants, such as from motor burn-outs or high acid levels, do not imply releases when the old refrigerant is recovered for reclaim or disposal.

A fourth error partially offsets the first three, in the majority of studies, namely omission of *upstream* losses. This term refers to fugitive emissions in manufacturing, packaging, repackaging in distribution, transportation, storage, and handling of the refrigerant before use, including amortization of associated catastrophic losses in transportation, distribution, and storage accidents. In short, it accounts for all releases of the refrigerant prior to its introduction into equipment for use. Although it is a small fraction of the total for the container sizes used for large chillers, this adjustment can be appreciable for some ACR applications. As an example, upstream losses may exceed 25% in small containers for consumer use to “top off” the charge in automobile air conditioners.

Future emissions are likely to be reduced to or less than the low levels projected by Calm (1993) by the improvements discussed below. Those levels were determined through a survey of the product development and engineering departments of equipment manufacturers. The results are supported by proprietary data obtained for more than 4000 chillers.

Changes to Reduce Refrigerant Releases

The preceding discussion summarizes remarkable reductions in refrigerant losses in the last two decades, typically by factors exceeding ten over the life of a chiller. Such dramatic decreases required hundreds of modification in the design, manufacture, and service of chillers. Some of the key changes were:

SEALS AND JOINTS

- design changes to minimize the number of joints in refrigerant circuits
- replacement of flared and other mechanical connections with brazed connections

- augmentation of threaded joints with o-rings
- use of new gasket materials
- augmentation of flat face gaskets with silicone beads
- replacement or augmentation of gaskets and o-rings with adhesive sealants

PURGE SYSTEMS

- use of high performance (generally condensing) purges
- use of vapor recovery systems in purge venting

SERVICE

- incorporation of on-board refrigerant storage or means for charge recovery during service
- introduction of, and in some countries requirements for, refrigerant recovery equipment
- use of cylinders instead of drums to transport and store low pressure refrigerants
- shift from scheduled lubricant changes to when needed
- increased diagnostic measures in preventative maintenance
- license requirements for technicians
- education and training of technicians
- increasing role of manufacturers in service operations

OTHER CHANGES

- use of enhanced heat transfer surfaces, reducing internal volumes and charge amount
- design changes to extend service intervals, thereby avoiding service-related releases
- design changes to reduce failures and extend equipment life
- manufacturing advances
- factory tests
- use of leak detectors
- microcomputer control of operation
- bearing advances to reduce or eliminate compressor lubricants and refrigerant losses during oil changes
- regulations to prohibit intentional venting
- regulations to require repairs when refrigerant make-up exceeds prescribed thresholds

This list of technology, service, and regulatory advances to reduce emissions suggests a revolution, rather than evolution, in measures to reduce refrigerant releases. Moreover, this list highlights only the key changes; there were many others.

The measures to reduce refrigerant releases are not limited to CFCs, HCFCs, HFCs, and PFCs. Most of them also are applicable to ammonia, carbon dioxide, hydrocarbons, water, and other nonfluorocarbon refrigerants. Their release could increase flammability or toxicity hazards, risk pressure injuries, degrade system reliability, or exacerbate other environmental problems. For example, hydrocarbon emissions may contribute to local smog formation; such releases will be concentrated in urban areas in which smog problems are most acute. Released ammonia that is washed into surface water by rain is highly toxic to aquatic life. And most importantly, loss of refrigerant from vapor-compression machines, or air leaks into subatmospheric equipment, reduces operating efficiency and thereby increases energy use and GHG emissions.

Efficiency and Warming Impacts

Figure 1 shows the consequences of reduced emissions, both refrigerant and energy-related, from centrifugal chillers on GHG emissions. The data shown are for 1750 kW (500 ton) R-11 and R-123 chillers. Approximately 60% of the centrifugal chillers installed in the years shown used these refrigerant. Similar conclusions can be drawn for replacement of R-12 with R-134a for the same time frame, although the absolute emissions both start and end at higher levels. The underlying analyses, commonly described as *total equivalent warming impact* (TEWI) analyses, and data are detailed in Calm (1993) and Calm and Didion (1997). The only change herein is recalculation with the refrigerant global warming potentials (GWPs) from the latest scientific assessment (WMO, 1999). The updated GWPs for the four cited refrigerants, namely R-11, R-12, R-123, and R-134a, for 100-year integration were increased from 3800, 8100, 90, and 1300 relative to CO₂ to 4600, 10600, 120, and 1600, respectively.

R-11 dominated in centrifugal chillers almost since its introduction. Refrigerant losses were high; they often exceeded 15% of the total charge each year, as shown in figure 1 for 1985. Small efficiency gains appeared by 1990, but more significant gains were introduced in system tightening and improved purge technologies. Figure 1 shows the resultant drop in impacts from emissions. R-123 use also had begun, though the first machines – essentially R-11 designs with materials changes for compatibility – yielded 14-16% lower efficiency. The direct warming impact of R-123 emissions is barely visible, owing to the difference in GWPs, a decrease of more than 97%.

Release reductions continued both by equipment tightening and improved service practices, as discussed above. By 1992, the last year in which R-11 chillers were manufactured for domestic use in the United States, net refrigerant emissions for machines of comparable capacities were half of those in 1985 and before. These reductions offer several benefits beyond reduced global warming. They also lower the impact on ozone depletion. The ozone depletion potential (ODP) and GWP of a chemical only are relevant for the portion that is released. Refrigerant that does not escape, and is recovered for reuse or safe disposal, does not harm the environment. Reduced losses also eliminate the need for makeup, thereby saving other resources and lowering costs, improving safety, and avoiding performance losses from insufficient refrigerant charge.

Figure 1 also shows the dramatic improvements made by 1995 in R-123 chiller optimization, leading to higher

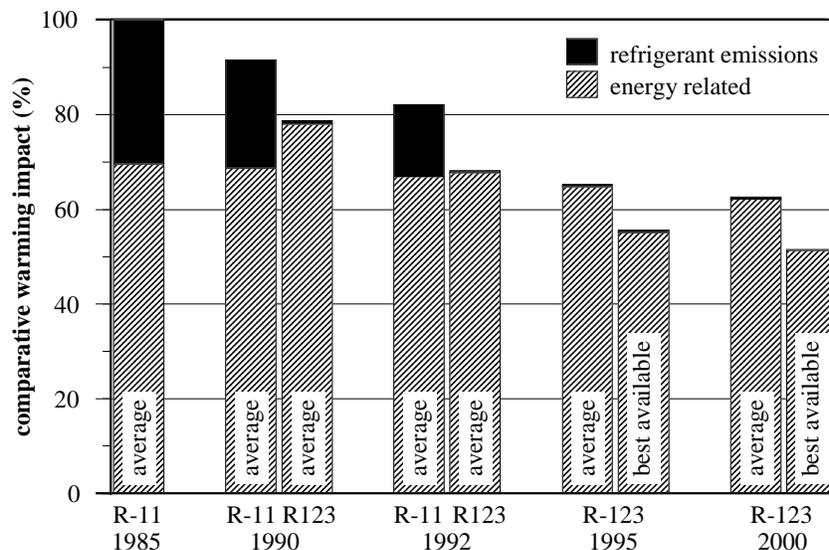


Figure 1: Progression and projection for comparative warming impacts (relative TEWIs) for centrifugal chillers for 1985-2000 with replacement of R-123 for R-11

practical efficiency than available with the retired R-11 designs. This achievement, and subsequent further gains, are all the more impressive since R-11 holds a small theoretical efficiency advantage over R-123 (Calm and Didion, 1997).

Further improvements in performance followed and will continue, but the pace will slow as gains approach theoretical limits. Coupled with emission reductions and the lower GWPs of R-22, R-123, and R-134a, the best chillers in 1995 reduced net global warming impacts by approximately 45% compared to typical machines a decade earlier. This fraction will exceed 48% by the year 2000 as shown in figure 1.

Figure 2 illustrates the comparative magnitudes of warming impacts from emission of refrigerants and use of energy by water-cooled chillers. The efficiencies used in this example were the highest commercially available in late 1996, as determined by an industry survey (ARI, 1996). The survey was restricted to equipment with certified performance ratings, and the submissions were verified. Once again, the analyses are explained by Calm and Didion (1997), but were updated herein with the new GWP data cited above (R-22 increased from 1500 to 1900 on a consistent basis).

As shown in figure 2, the direct effect of refrigerant emissions amounts to only 3-5% of the annual total for chillers using R-22, which has the highest GWP of the three refrigerants shown. These fractions drop to approximately 3% with R-134a and to less than 0.2% with R-123, which also offers the lowest energy-related impact based on its efficiency.

From a comparative warming or TEWI perspective, phaseout of the HCFCs and HFCs provides only a small gain in the refrigerant-related warming component for chillers with low refrigerant releases. There is far greater opportunity in efficiency improvement. The same conclusion holds true for most other air-conditioning and refrigeration products as well. Two exceptions are mobile air conditioners and supermarket refrigeration systems. They have high loss rates, but their energy-related impacts still dominate over those from refrigerant releases.

Calm and Didion (1997) and Calm (1999) summarize efficiency limits in theoretical cycles for current and candidate refrigerants. As shown, neither ammonia nor the hydrocarbons match the efficiencies of the best fluorochemical options. Such comparisons strongly suggest that the fluorochemical refrigerants be retained to reduce global warming, until comparable or superior efficiencies can be demonstrated without them and without com-

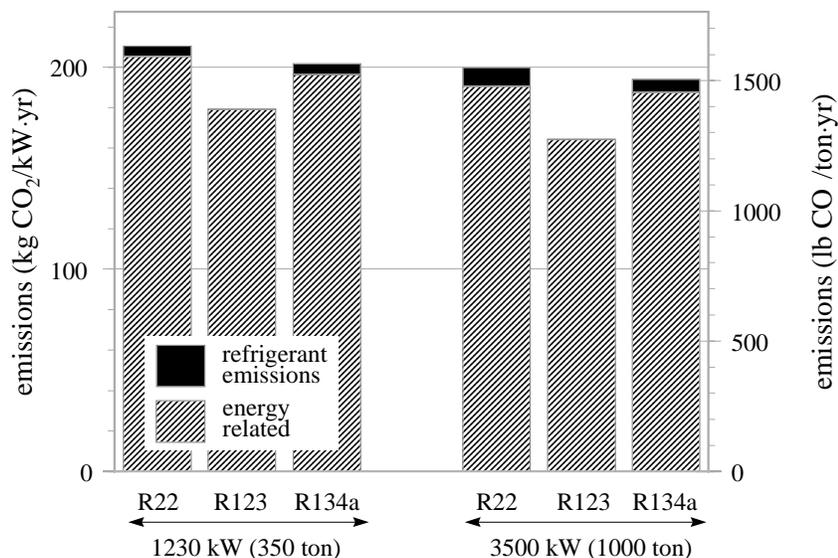


Figure 2: Greenhouse gas emissions (expressed as equivalent carbon dioxide) per unit of cooling per year – TEWI – for the best available chillers in two representative capacities

promising occupant safety. To avoid any misinterpretation, there are applications where ammonia and hydrocarbons offer advantages, but nobody should infer that they are similarly attractive in all refrigerant uses. Ammonia already is widely used in food and beverage processing and storage. One hydrocarbon option that holds promise, but which is not frequently mentioned, is ethane (R-170) for use in ultra-low temperature systems with small charge sizes. Ethane's efficiency is low at chiller operating conditions, which are near its critical point temperature. That is not the case for extremely-low temperatures, where high GWP fluids (primarily CFCs, PFCs, and blends of them) are common. R-601 (n-pentane) and its isomers offer both high efficiency and low-pressure operation at chiller conditions, but they are highly flammable and pose a considerable safety risk in the quantities needed by large chillers.

Calm and Didion (1997) present a detailed analysis that shows that there are no *ideal* refrigerants. Such fluids would offer zero ozone depletion, zero global warming, high efficiency, very low toxicity, and no flammability – even without practical constraints such as cost, materials compatibility, and chemical and thermal stability. The referenced paper also provides a rationale based on thermodynamics and chemical composition to suggest that the elusive ideal refrigerant probably does not exist.

Necessary Refrigerant Compromises

Most first generation refrigerants (1830s-1930s, selected based on availability and thermal suitability) were retired for safety reasons. Some, such as ammonia and hydrocarbons, survived or were later revived for limited applications in which their risks were manageable, such as industrial or small-charge systems (see Calm and Didion, 1997, for elaboration). Most second generation refrigerants (1930s-1990s, selected for safety, durability, and performance) have been or are being retired to protect the stratospheric ozone layer. The criteria for third generation refrigerants (“alternative refrigerants”) include both safety and environmental issues. Whereas the first generation lasted approximately 100 years and the second approximately 60, care is needed in dismissing options with minor defects if manageable. The third generation will be more vulnerable as the global population increases, industrial and economic development expands, and environmental understanding increases. These considerations demand greater attention to atmospheric lifetime to ensure that we not repeat the error made with CFCs and halons, namely releasing large quantities of long-lived compounds before we discover their impacts. Likewise, far more attention is needed to containment and recycling instead of phaseout.

There is no common denominator to equate the demerits of ozone depletion and global warming. It is clear, however, that a 13-19% increase in global warming to switch from R-123 to R-134a, at the best performance levels, is more significant than a 0.002% or lower peak impact on ozone depletion (Wuebbles and Calm, 1997; Calm, Wuebbles, and Jain, 1999). This comparison is more dramatic for newer data, namely increases of 14-20% in carbon equivalent GHG emissions versus less than a 0.001% increase in peak CBL. The new comparison employs efficiency improvements since 1996 and reduced refrigerant release rates, both of which are evident in figure 1. It combines them with updated ODP values and new GWP data (WMO, 1999). Moreover, four factors increase the importance of the comparison. First, correction is underway for ozone depletion (Wuebbles and Calm, 1997; WMO, 1999). Second, ozone depletion will not be discernibly increased with a reprieve for R-123 (Calm, Wuebbles, and Jain, 1999), which has an ODP of only 0.012 and atmospheric lifetime of 1.4 yr (WMO, 1999). Third, recovery of the ozone layer will not be retarded with a reprieve for R-123 (Wuebbles and Calm, 1997; Calm, Wuebbles, and Jain, 1999). And fourth, the options to adequately address global warming are far more limited, and a reprieve for R-123 is one of them (Calm and Didion, 1997; Calm, Wuebbles, and Jain, 1999).

It is highly probable that HCFC-123 and possibly other short-lived CFC replacements would have survived restrictions to protect stratospheric ozone had the global warming response occurred first. With keener awareness of the more-limited options remaining (Wuebbles and Calm, 1997), the framers of the Montreal Protocol might have been more cautious in rejecting chemicals with indiscernible ozone impacts but offsetting environmental

benefits. Likewise, phaseout of HFCs from chiller use for very small benefits in direct (refrigerant-related) warming impacts at the expense of greater CO₂ and N₂O emissions will increase rather than decrease net warming.

The key distinction that makes most ACR applications, and especially chillers, unique from other HCFC, HFC, and PFC uses is that the refrigerant is used in closed systems with very low life-cycle release rates. Most of the refrigerant can be, and is being, recovered upon ultimate equipment retirement. A second difference, at least for HCFC-123 and HFCs, is that abandoning these proven options would increase the GHG emissions from associated energy use.

Conclusions

Historic releases of refrigerants from centrifugal chillers have been dramatically reduced from annualized (amortizing initial and disposal losses) rates of 8-37 %/yr to less than – or significantly less than – 1 %/yr. The refrigerant needs for make-up in old chillers far exceeded those for initial charging, amounting to more than ten full charges over the operating life in the worst cases. By contrast, more than three-quarters of the original charge can be recovered for re-use or safe disposal when current equipment reaches retirement; that fraction exceeds 90% in the best systems. On average, the lifetime refrigerant needs for chillers have been reduced more than tenfold.

Most of the technologies applied to achieve these loss reductions also can be applied in smaller ACR equipment. The driving forces for the changes in large chillers was economics, including competitive marketing advantage, and growing environmental awareness.

The importance of a refrigerant's ODP or GWP diminishes with very low losses. For refrigerants with low ODP and low GWP, the most damaging environmental effect from refrigerant losses is suboptimal operation resulting in increased energy use and, thereby, increased emission of CO₂ and other GHGs to power the system. Suboptimal efficiency thus exacerbates climate change even with zero-GWP refrigerants.

Any refrigerant substitution that lowers overall efficiency is likely to have more adverse impact than benefit based on net global warming impacts (e.g., life-cycle GHG emissions or TEWI).

Phaseout of R-123 – the most-widely used refrigerant in centrifugal chillers today – as an HCFC will increase HFC use, and therefore HFC releases, but more importantly will significantly increase global warming with lowered operating efficiencies for no discernible benefit in stratospheric ozone protection. An integrated assessment of ozone protection, climate change, local environmental and safety issues, and the likelihood of future environmental concerns suggests the need for distinction between short-lived, low-ODP chemical and those with high ODPs, particularly in low-emission applications such as R-123 in chillers.

Whereas no ideal refrigerants exist, care is needed to not dismiss options with minor flaws without examination of their net environmental advantages.

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